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Introduction to the Special Issue on Inverse Methods in Electromagnetics

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Abstract—**Inverse methods have become a fundamental tool in the physical sciences for remotely sensing unknown objects and reconstructing their physical properties. The objective of this special issue is to present an overview of this important rapidly emerging discipline and to provide examples of the wide scope of methods used to investigate inverse problems in electromagnetics, ranging from purely theoretical considerations to some very practical problems.**

I. GENERAL OVERVIEW

Inverse methods have been used to investigate a vast range of problems in the engineering sciences. They have been developed in many otherwise diverse fields of physical sciences where the characteristics of a medium are estimated from experimental data in a given situation. It is known that some techniques used in one field are identical, at least in principle, to those used in another entirely different area. These interdisciplinary applications of inversion techniques are drawing increasing attention and, therefore, we consider it relevant to open this special issue with a brief overview of several references which may be useful to the general reader.

An extensive survey covering many fields in which inverse methods may be applied is compiled in a NASA memorandum by Colin [20]. This has proven to be a major source for generating rapid interest in other related areas; more succinct introductions to inverse methods have been given by Newton [62], Keller [42], and Parker [63]. Theoretical developments have been summarized by Sabatier [68] and a thorough literature survey of many aspects of inverse methods in electromagnetics has been presented by Boerner [10], whereas inverse source and scattering problems in optics recently were treated in Baltes [4], [5].

Mathematical Treatments

A common approach based upon the linearization of the inverse problem with the sought-after quantity represented as a small perturbation about an assumed value, leads to an underdetermined linear system. In this connection the mathematics of generalized inverses [51] was employed side by side with the mathematics of profile inversion and an excellent treatment with applications was edited by Nashed [60] in which particular emphasis is given to the Moore–Penrose inverse. Closely related with inverse problems are methods of regularization [39], [73] which are well discussed in tutorial papers by Deschamps and Cabayan [25], as well as by Wegrowicz [79], Twomey [75], and in recent East European publications [74], [34], [39], [73]. In spite of the techniques developed here, the linearized approach is highly inadequate. The complete nonlinear problem and its correction to the linearized problem has been analyzed most recently by Weston [81], [82].

Of basic importance to the inverse differential geometry is the Minkowski problem [59] in which a transform procedure is introduced to map the topological image of a closed convex surface onto the unit sphere of directions [27] in terms of principal curvatures. In many two- and/or three-dimensional wave transmission and reflection profile reconstruction methods, the theory of reconstruction from projections becomes of fundamental importance which was introduced by Lorentz [76] and Radon [65], who established all the basic relationships existing between transforms in image, projection, and Fourier space. The theory is well treated by John [43], whereas implementations and applications of Radon's projection theory were given recently in Herman [37].

In one way or another most inverse methods used in remote sensing deal with the inversion of the wave equation [20], [81], which for the case of radio waves was discussed in detail, for example, in Budden [15], Chernov [18], and most recently in Ishimaru [38], where in many solutions use is made of the Abel transform [77] and of the classical Wentzel–Kramer–Brillouin (WKB) approximation [40] in problems of a slowly varying profile in (r). Considerable extensions of these inversion methods were obtained for the inhomogeneous wave equation in quantum mechanics known as the Gelfand–Levitan–Marchenko [28], [1] procedure. Implementations and applications more recently were highlighted in review articles given, for example, in [20], [68], [61], [17], [28], [24], [74]. The case where the scattering data are expressed as rational functions has special interest, since closed-form expressions for the scattering potential can be obtained; see Kay [45] and Jordan and Ahn [44]. It should be noted that extensions of the Gelfand–Levitan–Marchenko procedure have become of considerable interest in the solution of nonlinear problems [69], particularly solitary wave mechanics [57]; and in an excellent tutorial paper Lax [52] has developed systematically the relationship between solitary waves with the direct, the time evolution, and the inverse problems of scattering.

Geophysical Inverse Problem

Another startling extension of the regularization method may be seen in the optimum strategy method applicable to the inversion of limited data which was introduced by Backus and Gilbert [2], [3] dealing with the geophysical inverse problem. This method has since found many applications [29] and was found well suited to treat a class of nonlinear inverse problems of the solitary wave type [69]. We call the reader's attention to Barcilon's [6] outstanding tutorial review, in which some fundamental mathematical aspects of geophysical inverse problems are discussed in a simplified presentation.

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Today geophysical inverse methods are widely used in exploration seismology [7], [8], [19], [26], [29], [39], [41], [70], where in essence the time of arrival of seismic pulses at various locations, generated by sources at different locations, i.e., the "wave equation migration [19] method," is used to formulate the problem in terms on nonlinear functionals. Considerable advances have been made in spectral analysis [8] and deconvolution techniques [70] which also should be very powerful methods in other fields of remote sensing where signal versus clutter suppression becomes paramount. Vertical seismic profiling is an extension of the scalar methods and permits inverse solutions for reflection and refraction seismology in elastic media where in addition to p, s-wave components also need to be taken into consideration [30].

Remote Sensing

Inverse methods are also an integral part of aeronomic remote sensing [20], [23], [38], [72], [33], [56] using both passive and active wave sounding where usually the Born and Rytov approximations for slowly varying index profiles [10] are relevant. Whereas in the microwave region coherent methods developed in radar are more likely to be used [30], [42], [48], [50], in the infrared and optical regions incoherent properties need to be taken into consideration as well, and we recall [22], [16], [42]. Specifically, we refer to Baltes [4], [5] in which most recent monographs on inverse problems in optics have been presented. Image formation from coherence functions is also a basic inverse problem in astronomy [78]. We should mention here that Radon's theory of image reconstruction from projections also has become a very useful tool in radio astronomy [37] as was first shown by Bracewell [13], [14], and similarly various interferometric and holographic image reconstruction methods [48], [78] are relevant.

Medical Imaging

Inverse methods always have played, and more explicitly, are playing an increasing role in medical imaging [64], where in addition to X-ray radiography and its most recent extensions of computer-assisted tomography (CAT)-scan [37], [31] we need to refer to methods of ultrasonic imaging [54], [58] as well as microwave imaging [49]. The case of inverse methods in medical diagnosis is expanding rapidly[12]; and it is safe to say that diagnosis of biological systems by nonionizing electromagnetic as well as acoustic waves is on a steady increase [54], [55], [80], and applicable imaging procedures require solutions to the inverse problem of wave propagation in strongly inhomogeneous media [12].

Radar and Imaging

Before introducing inverse methods directly applicable in electromagnetics within the *m*-to-*mm* wave region, we shall here refer to some major relevant monographs and books dealing with sonar, radar, and lidar [48], [32], [71], [66], since theoretical analysis of these remote ranging and sensing schemes systematically led to the rapid growth of inverse diffraction, inverse scattering, and imaging theories based on radar cross-section analyses [21], [67]. Specifically, we need to mention that inverse methods are implicitly used in synthetic aperture radar [36], [42] and other target size and shape adaptive imaging radars and scatterometers [32].

II. INVERSE METHODS IN ELECTROMAGNETICS

At present there is no generally accepted definition of the inverse problem, although several descriptions have been given, e.g., [20], [46], [63], [9], [6]. We shall attempt to present one distinction between the direct and inverse problems of wave scattering meaningful in remote sensing problems:

> Whereas, on the one hand, in the direct problem of electromagnetic scattering total *a priori* information on the size, shape and material constitutents of an object, together with the relative geometry of the incident field vector and the object coordinate system, are given and the scattered field vector is to be determined everywhere over the total frequency or time domain; on the other hand, the inverse problem is to reconstruct the size, shape and material characteristics of an *a priori* unknown scattering object from the knowledge of the incident field vector and the resulting scattered field data.

This distinction [10] has been given in terms of vector (electromagnetic) wave scattering; it can also be applied to the scalar (acoustic) and tensor (acoustoelastic) cases.

Considering the complexity of the boundary conditions and constitutive relations, there apparently will not exist an exact general inverse scattering theory as described above that can yield practical solutions in a finite number of computations [11]. Rather than initially seeking exact self-consistent solutions for the general three-dimensional inverse problem, information can be obtained by studying simplified physical models and/or using approximate analytical techniques [10], [12].

III. ARRANGEMENT OF PAPERS AND KEYS TO CATEGORIES

The papers which comprise this special issue address a broad spectrum of inverse methods and provide both numerical and experimental results. These papers can be somewhat arbitrarily classified according to various criteria, as shown in Table I, where we have chosen six categories with keys indicated in parentheses.

1) *Nature of model*: *Scattering* (S) from targets [67], *propagation* (P) through inhomogeneous or random media [38], *imaging* (I) of targets by processing the scattering data [30], or the *general* (G) inverse problem.

2) *Dimensionality of the physical model*: The *one-dimensional* (1) scattering model is an idealized example that posses-ses a complete exact solution; physical insight into the relations between the scattering data and the refractive-index profile can be obtained by considering this inverse scattering problem [44], [45].

Surface scattering (2) is an inverse problem which has important applications in the remote sensing of natural surfaces (terrain and oceans) and optical systems [14]. Scattering by *three-dimensional* (3) convex targets has obvious importance for radar and sonar applications [43], [48]. In some cases [52] certain inverse theories are applicable to the general *n-dim* (n) case.

3) *Frequency (F)/Time (T)*: Various approximations with respect to the relative wavelengths are being considered. Low-frequency, resonant-frequency, and optical-frequency approximations [21] can provide simplified analyses. Related to these questions are those of transient scattering in the time domain [47], [9] and the availability of broad or narrow band scattering data [53] (*mixed* (M)).

4) *Polarization*: While it is convenient to study the analytical properties in terms of *scalar theories* (K), electromagnetic scattering problems will, in general, require extension to the *vector case* (V). Here polarization effects must be considered [11].

TABLE I

Authors	Categories 1	2	3	4	5	6
H. P. Baltes and H. A. Ferwerda	I	3	F	K	L	R
R. H. T. Bates and R. P. Millane	S	3	T	V	L	D
C. L. Bennett	S	3	T	V	L	D
C. L. Bennett and J. P. Toomey	S	3	T	V	L	D
H. Bertero and C. DeMol	I	1	F	V	L	R
R. M. Bevensee	S	1	F	K	L	R
W. M. Boerner, M. B. El-Arini, C. Y. Chan, and P. Mastories	G	3	M	V	L	Q
W. M. Boerner, C. M. Ho, and B. Y. Foo	I	3	M	V	L	D
W. M. Boerner, A. K. Jordan, and I. W. Kay	G	n	M	V	L	Q
J. C. Bolomey, D. Lesselier, C. Pichot, and W. Tabbara	S	3	T	V	L	D
C. K. Chan and N. H. Farhat	I	3	F	V	L	D
L. C. Chan, L. Peters, and D. L. Moffatt	S	3	F	V	L	D
L. C. Chan, L. Peters, and D. L. Moffatt (Subsurface Radar Target Imaging Estimates)	S	3	T	V	L	D
S. K. Chaudhuri	S	2	M	K	L	D
S. Coen, K. K. Mei, and D. J. Angelakos	P	1	F	K	U	R
D. Colton	S	3	T	V	U	D
L. E. Corey and E. B. Joy	S	2	T	V	U	D
A. K. Datta and S. C. Som	S	2	F	V	U	D
M. Fiddy, G. Ross, and M. Nieto-Vesperinas	P	1	F	K	U	R
Y. Furuhama and T. Ihara	P	1	F	V	L	D
G. Gaunaurd and H. Überall	S	3	T	V	U	D
F. D. Gross and J. D. Young	I	3	T	K	L	D
B. J. Hoenders	I	3	F	K	L	R
E. M. Kennaugh (Opening Remarks)	G	3	T	V	U	D
E. M. Kennaugh (Polarization Dependence of RCS)	S	3	T	V	L	D
E. M. Kennaugh (The *K*-Pulse Concept)	S	3	T	V	L	D
R. J. Krueger	P	1	F	K	U	D
J. McFee and Y. Das	I	3	F	V	L	R
D. L. Moffatt	S	3	T	V	L	D
D. L. Moffatt, J. D. Young, A. A. Ksienski, H. Lin, and C. M. Rhoads	S	3	T	V	L	D
M. Z. Nashed	G	3	M	K	L	D
R. D. Radcliff and C. A. Balanis	S	3	T	V	L	R
M. H. Reilly and A. K. Jordan	P	1	F	K	U	D
A. Roger	P	1	F	K	U	D
T. K. Sarkar, D. D. Weiner, and V. K. Jain	S	1	F	K	U	D
L. S. Taylor	P	1	F	K	U	R
A. G. Tijhuis	P	1	T	K	U	D
G. Tricoles, E. L. Rope, and R. A. Hayward	S	3	F	V	L	D
P. F. Wacker	S	3	M	V	L	D
J. S. Yu	P	1	T	K	L	D
J. S. Yu and J. W. Williams	I	3	F	V	U	R

Key to Categories

1) Type of Problem
- S Scattering
- P Propagation
- I Imaging
- G General

2) Dimensionality
- 1
- 2
- 3
- n

3) Temporal Space
- F Frequency
- T Time
- M Mixed Time Frequency

4) Polarization
- K Scalar
- V Vector

5) Data Format
- U Unlimited
- L Limited

6) Statistics
- D Deterministic
- R Random
- Q Quasi-coherent

5) *Data limitations*: In regard to the availability of measurement data with respect to aspect, frequency, and polarization, we may state that narrow band (i.e., approaching continuous wave (CW)/monostatic case) techniques require multiple aspect data covering the total unit sphere of directions; whereas, for broad-band methods shape and size reconstruction of targets becomes feasible given data for a few or only one aspect with increasing bandwidth (i.e., approaching the ideal transient case) covering the low frequency, across resonance, up to high-frequency regions of the target cross section under consideration [10]: *unlimited data* (U), *limited data* (L).

6) *Statistical properties*: Scattering by volume distributions of particles involve inverse problems to determine the statistical distributions of partcicle sizes, shapes, and materials; propagation in *random media* (R) is an important application [38]. This is distinguished from *deterministic* (D), or *quasi-coherent* (Q) inverse problems.

IV. EDITORS' COMMENTS

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